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Dinoflagellate cysts from the 'Anthropocene' of Gullmar Fjord, west coast of Sweden and their potential for monitoring climate change

Rex Harland [a,*], Irina Polovodova Asteman [b,c], Kjell Nordberg [b]

[a] 50 Long Acre, Bingham, Nottingham NG13 8AH, UK
[b] Department of Marine Sciences, University of Gothenburg, P.O. Box 461, SE 405 30, Sweden
[c] Currently at Marin Mätteknik (MMT) Sweden AB, Sven Källfelts Gata 11, 42671 Gothenburg, Sweden

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ABSTRACT

A small set of samples from Gullmar Fjord, on the west coast of Sweden, together with published data, has allowed the investigation of the 'Anthropocene' within the fjord. The dinoflagellate cyst record and its statistical analysis fails to show any marked changes within the assemblages either across the proposed boundary or indeed within the youngest sediments at the top of the sequence. However there are some small scale differences in the youngest assemblages that are of interest. In particular these include quantitative shifts in the numbers of some of the species especially *Pentapharsodinium dalei*, which may be indicative of somewhat cooler environments linked to the winter North Atlantic Oscillation (NAO) and extra availability of nutrients from Ekman pumping. These small scale shifts in the assemblages point to clear dynamism within the phytoplankton populations reacting to both anthropogenic and natural environmental change; evidence of the complexity of the system.
The proven utility of dinoflagellate cysts in charting climate change throughout both the Pleistocene and Holocene within Gullmar Fjord, and elsewhere along the west coast of Sweden is in marked contrast to the little change at the 'Anthropocene' boundary. Nonetheless the geographical position of the fjords along the Skagerrak are ideal to monitor environmental change within the North Sea basin and perhaps further afield in the eastern North Atlantic Ocean; especially since further climate change threatens regime change within the marine environment affecting tourism, industry and mariculture along the coast.

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1. Introduction

Over recent years there has been concern over the changing environments along the west coast of Sweden. This has been manifest in the occurrence of periods of eutrophication, changes in salinity regimes, the failure of the fishing industry in places and difficulties with ensuing water quality. The causes of such changes involve a whole series of factors complex in nature and difficult to disentangle. Indeed interpretations of the various evidence has produced some controversy (Harland et al., 2006; Dale, 2009) over the years but has highlighted the need for further research to understand better the factors involved.

The sediments involved in this study were deposited within the late Holocene epoch and across the suggested Holocene/Anthropocene boundary and are, therefore, of great interest in analysing environmental change over this time period. The Holocene, formally the second epoch of the Quaternary Period and the most recent interval of geological time, currently includes the present day. The base of the Holocene is often difficult to define, but is fundamentally based upon evidence of contrasting climatic conditions. Indeed Walker et al. (2009) proposed that the base be defined on the basis of the NGRIP ice core reflecting the first signs of climate warming at the end of the Younger Dryas/Greenland Stadial 1 cold phase. This boundary is taken at 11,700 yr b2K (before 2000 CE) ± 99 yr at two standard deviations.

Various attempts have been made to sub-divide the Holocene. The presence of climatic fluctuations within the Holocene provides a climatostratigraphy on a millennial to centennial or even decadal timescales. For example within the Subatlantic, i.e. the last 2500 yr BP, the recognition of several climatic phases such as the Roman Warm Period, the Medieval Warm Period or Medieval Climatic Anomaly (MCA) and the Little Ice Age (LIA) (e.g. Lamb, 1995; Polovodova Asteman et al., 2018) are important subdivisions of the Holocene as summer solar insolation declines (Wanner et al., 2011). Also involved are changes in solar activity (Mauquoy et al., 2002), volcanism (Sicre et al., 2011; Miller et al., 2012), the state of the North Atlantic Oscillation (Trouet et al., 2009) and changes in the Gulf Stream (Lund et al., 2006). In addition, changes in the Atlantic Meridional Overturning Circulation (AMOC) are implicated with significant climate impacts throughout the Holocene (Hoogakker et al., 2011). The increasing precision being brought to the study of the Holocene potentially increases our knowledge of the complexity of climate change and the prediction of possible future scenarios. This increased precision and complexity has now led climate

* Corresponding author.
E-mail address: rex.harland@ntlworld.com (R. Harland).

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scientists to regard human activity as having a profound effect on global Earth processes (Crutzen and Stoermer, 2000; Crutzen, 2002).

In recent years there has been a proposal to establish a new geological period, the Anthropocene, for the very latest sediments being deposited in the geological record. The basic premise for the establishment of the Anthropocene is that humankind has had such an influence on world geological processes that due recognition should be given to its impact on the global environment. The term was first introduced by Crutzen and Stoermer (2000) and has become widely used informally; it is now under consideration as a new formal unit by the International Commission on Stratigraphy (Zalasiewicz et al., 2017). Any new stratigraphic unit needs an acceptable lower boundary separating it from sediments below and demonstrating substantial change in the Earth's processes. Controversy has ensued over the concepts involved in the establishment of the Anthropocene and its definition. However the lower boundary needs to be globally synchronous and recognised around the world in a variety of geological settings. Any definition must necessarily address habitat modifications within the marine biota as an important factor within the global environment. Several possibilities have been discussed including human impact on habitat, links to the industrial revolution, increased population growth following the Second World War as in the 'Great Acceleration' (Steffen et al., 2007) and a significant change in the rate of biotic change (Wilkinson et al., 2014). Much of these factors occur in the mid-20th Century at around the Alamogordo, New Mexico atomic test explosions in 1945; this level is proposed for the lower boundary by Zalasiewicz et al. (2014). A formal proposal is to be submitted to the Subcommision on Quaternary Stratigraphy for further consideration (Zalasiewicz et al., 2017).

Over the last 20 years or so various and diverse research was published on sediments preserved within the fjords along the west coast of Sweden. This is a particularly important region used for tourism, mariculture and industry. The research has revealed a surprising complexity to the environmental history of the area. In particular detailed dinoflagellate cyst analysis has been completed on a series of fjords including Koljöfjord (Nordberg et al., 2001; Harland et al., 2004a,b; Filipsson et al., 2005), Gullmar Fjord (Harland et al., 2006; Harland et al., 2010; Harland et al., 2013b), Havstensfjord (Harland et al., 2013a), Dynekilen (Harland et al., 2013a) and Sannäsfjord (Harland et al., 2013a; Björk et al., 2017). In summary it has proved difficult to separate the influences of pollution and other anthropomorphic changes from those arising from alterations in the Earth's orbital parameters, the North Atlantic Oscillation and other natural drivers. All these factors effect change within the phytoplankton communities, including the impact on genetic diversity (Lundholm et al., 2017), and in themselves are co-dependent. Most recently oxygen depleted waters were newly discovered in Sannäsfjord; the causes of which were not altogether obvious, (Björk et al., 2017; Nordberg et al., 2017), but seemed to involve climate effects, changes in nutrient supply through increased precipitation and runoff, and a high abundance of filamentous algae.

In order to understand fully the present climate, and the controls that force change, it is crucial to detail the recent past. This is especially true given the concerns about present climate change, global warming and the marked increase of atmospheric carbon dioxide and other greenhouse gases since the start of global industrialisation. A CO_2 level of 400 ppm was breached in 2014 (397.34 ppm March 2013, http://www.esrl.noaa.gov/gmd/index.html, and is now running at 405.5 (2017) WMO Greenhouse Gas Bulletin (2018) 14, 1-9, in sharp contrast to the pre-industrialisation level of 280 ppm. This is the highest level ever measured over a 58-year instrumental record and in ice cores dating back some 800,000 years (Blunden and Arndt, 2017). Indeed there is increasing evidence that there have been biotic regime shift changes within the North Atlantic circulation in the 1920s and 1930s (Drinkwater, 2006) and more recently in the 1980s (Beaugrand et al., 2002; Reid et al., 2016). A study published by Barton et al. (2016) sought to model the biogeography of phytoplankton communities over historical time (1951–2000) and predicts changes into the future (2051–2100) involving both species and communities moving both spatially and temporally together with a certain amount of reassembling or shuffling. Poleward movement from the effect of environmental drivers may occur faster than previously estimated with many species moving in a northeastern direction. The phytoplankton communities appear to be primed for such a move with consequences to the marine regime within the global ocean. Similar changes have been seen before as the Earth moved from a glacial state to its present interglacial (Eynaud et al., 2012; Harland et al., 2016; Van Nieuwenhove et al., 2016).

Under these circumstances it is important to be aware of the current phytoplankton biogeography and to document change on at least an annual basis. This could be achieved ocean-wide or as a small scale study in a well-documented region where a system of close monitoring might well provide an early warning to these phytoplankton community shifts. The fact that dinoflagellates produce a cyst during their life cycle and that they have an extensive fossil record allows their use in the analysis of a decadal temporal record and clearly has a potential for establishing a possible baseline for future research along the west coast of Sweden.

1.1. Study area

Gullmar Fjord on the west coast of Sweden is ideally placed to provide an ultra-high resolution archive of sediment encompassing the Subatlantic phase of the Holocene, including the Roman Warm Period, the Medieval Warm Period and the Little Ice Age, and more importantly to this study, a record of modern warming (Harland et al., 2013b). It is one of the most studied marine areas in the world with the first hydrographical measurements being taken as early as 1869, and the site of one of the world's oldest marine research stations founded by the Royal Swedish Academy of Sciences in 1877. Research on the modern plankton continues today and offers important insights into primary production and trophic interaction (Lindahl et al., 2003; Tiselius et al., 2016).

In particular, Gullmar Fjord is a sill fjord and a site of net accumulation of sediment. Negligible tidal activity and high sedimentation rates of 0.7–1.4 cm a^{-1} (Filipsson and Nordberg, 2004) results in Gullmar Fjord becoming a high resolution environmental archive (Howe et al., 2010). In addition, the hydrography of the fjord, the stratified water column and the long residence time of the deep water together with high oxygen consumption from the decay of organic material results in hypoxia. In turn this affects the benthic communities and increases the likelihood of nil or low activity of the bottom macrobenthos leading to low bioturbation. These fine-grained sediments deposited in low oxygen environments, often relatively undisturbed by bioturbation and deposited in high accumulation environments are ideal for the preservation of a high-resolution dinoflagellate cyst temporal record (Harland et al., 2013b, 2006).

Finally Gullmar Fjord is ideally placed on the west coast of Sweden to pick up changes further afield given the presence of North Sea and Atlantic waters at depth (Björk and Nordberg, 2003), potentially introducing dinoflagellate cysts from areas other than the Skagerrak. In particular it is well-placed to monitor changes in the potential input of more south temperate dinoflagellate cysts and the lessening of cysts more usually found in the sub-arctic/arctic regions, together with any general shifts in the phytoplankton communities as a result of regime change. Hence the provision of a high-resolution temporal record over the last nine decades or so can only enhance the understanding of this short but important time interval, and has major potential for the prediction of future climate scenarios. In this paper we provide the dinoflagellate cyst record from two separate studies to detail changes within the late Holocene and 'Anthropocene' of the fjord and to provide a possible baseline for further monitoring research.

Gullmar Fjord, a sill fjord on the west coast of Sweden, north of Göteborg (Fig. 1) is some 30 km long and 2 km wide and has a

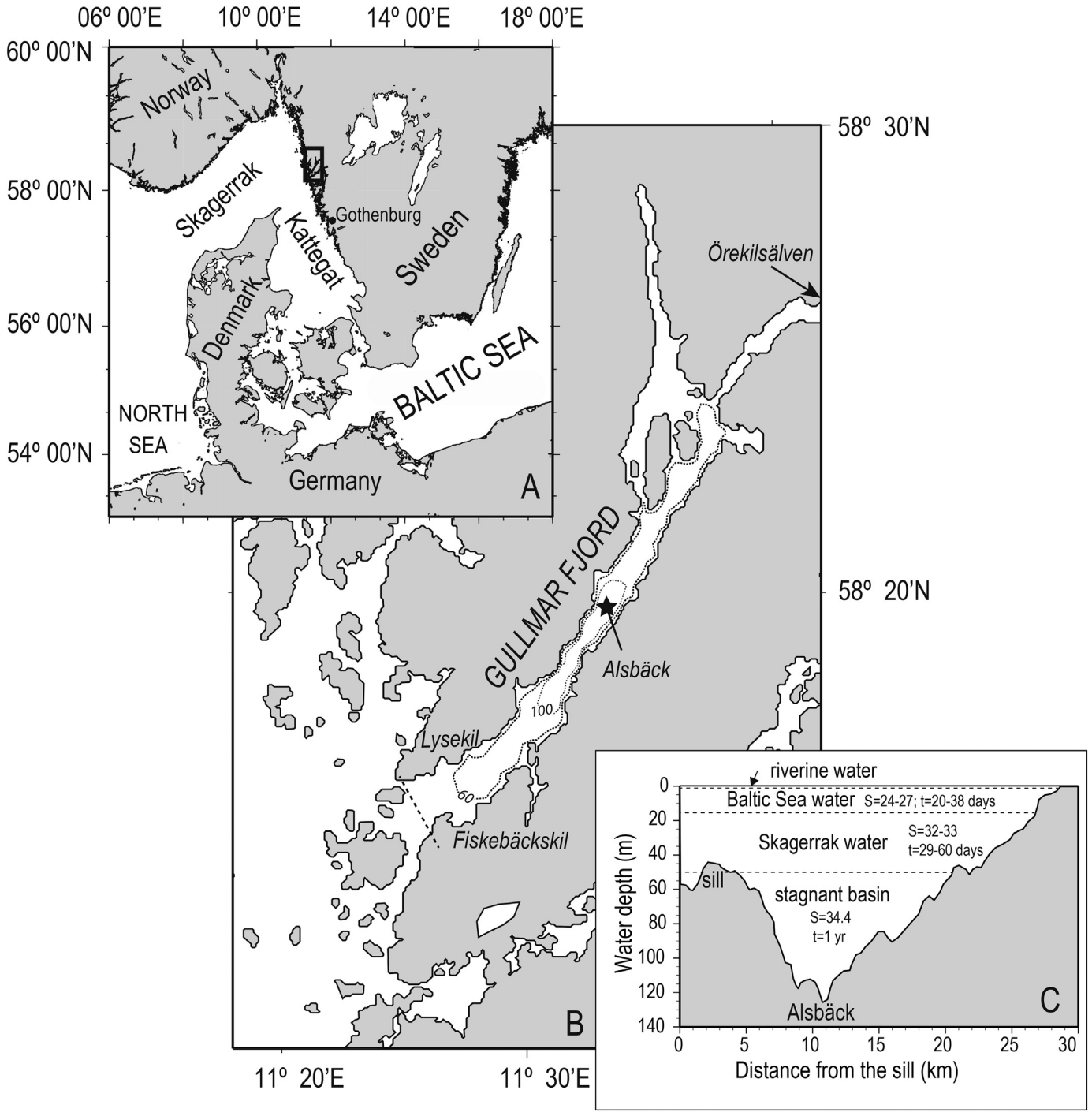

Fig. 1. Overview map of the study area. (A) A rectangle shows the location of Gullmar Fjord in the Skagerrak and North Sea region. (B) Overview of the Gullmar Fjord area; a star in the deepest basin (Alsbäck deep) indicates sampling site for cores G113-0113B, GA113-2Aa and GA113-2Ab; a dashed line in the outer fjord shows location of the sill. (C) Overview of water masses in the longitudinal profile of the Gullmar Fjord with data on salinity ranges (S) and residence times (t) typical for each water layer (after Arneborg, 2004).

maximum depth of 119 m. It is orientated NE/SW and opens into the Skagerrak across a sill at 42 m depth. The fjord is subjected to strong stratification with a pycnocline occurring between 15 and 20 m, separating upper low salinity waters (24–27 psu) from more saline waters (32–33 psu), and between 50 and 60 m separating the latter waters from the highly saline basin water (34–35 psu) in the deeper parts of the fjord (Lindahl et al., 1998; Arneborg, 2004). This stratification arises from the presence of low salinity Baltic water at the surface in the Skagerrak (Gustafsson, 1999; Björk and Nordberg, 2003) and higher salinity North Sea and North Atlantic water at depth. The deepest parts of the fjord, below 80 m, are occasionally subjected to hypoxic conditions during the autumn and winter providing the perfect environment to preserve the stratigraphic record without significant disturbance.

2. Materials and methods

Fourteen samples were taken from the core G113-0113B and were analysed for dinoflagellate cysts at 1 cm resolution. The core was taken on January 20 2012, using a Gemini corer from the Alsbäck Deep (Lat: 58° 17.570′ N, Lat: 11° 23.060′ E), see Fig. 1. The use of a Gemini corer provides a virtually undisturbed sediment/water interface and retrieves two sediment cores per deployment at 80 mm in diameter and

of some 20–50 cm in length. After collection the cores were X-rayed on board ship with an Andrex BV (155140 Kv/5 mA) portable machine before further investigations in the laboratory. The age model has been constructed based on a correlation with another core, Ga113-2Aa, taken at the same location in 1999 by the same sampling method and dated using ^{210}Pb and the constant rate of supply (CRS) model of Appleby and Oldfield (1978) together with well-known and documented benthic faunal change associated with a decline of foraminiferal fauna typical of the Skagerrak-Kattegat region and an increase of the opportunistic species *Stainforthia fusiformis* (Williamson, 1858) (Fig. 2). The position of the crossover between *S. fusiformis* and the Skagerrak-Kattegat fauna is dated to 1979/1980 (Filipsson and Nordberg, 2004) and allowed estimating sedimentation rate of 0.8 cm/yr for the core G113-0113B. For further details regarding ^{210}Pb dating see Filipsson and Nordberg (2004). A correlation of the dinoflagellate cyst data with the earlier studied core Ga113-2Ab (the twin for dated Ga113-2Aa from the same deployment) has allowed the two sequences to be amalgamated to facilitate the comparison between the two records and complete our analysis of the dinoflagellate cysts from 1930 to 2014 across the suggested Holocene/Anthropocene boundary placed at 1945 (Zalasiewicz et al., 2017).

The sediment recovered is an homogenous, organic-rich clay (Nordberg et al., 2000) and the samples were processed using the normal palynological techniques (Wood et al., 1996). No oxidation was performed during sample processing to prevent the differential loss of protoperidiniacean cysts (Dale, 1976; Zonneveld et al., 1997). Instead the samples were subjected to prolonged washing and filtering, together with the use of ultrasound to free the contained dinoflagellate cysts from the large amount of inherent amorphous organic material (AOM). The resulting residues were stained with Safranin, mounted in Elvacite and bonded to slides using Petrapoxy 154 resin, with a refractive index of 1.54. The samples were treated quantitatively to calculate the numbers of cysts per gram of sediment (see Harland, 1989; Harland et al., 2006) (Table 1).

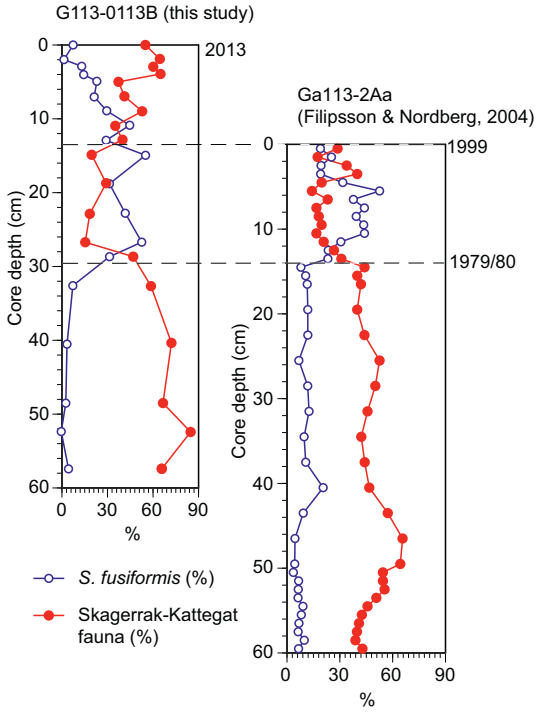

Fig. 2. Stratigraphic markers of a well-known faunal change in benthic foraminiferal faunas (Filipsson and Nordberg, 2004) and correlation between the cores G113-0113B and Ga113-2Aa, a twin core for the dinocyst-studied G113-2Ab (Harland et al., 2006), discussed herein. The position of the cross between *S. fusiformis* and the Skagerrak-Kattegat fauna is dated to 1979/1980 (Filipsson and Nordberg, 2004) and allowed estimating sedimentation rate of 0.8 cm/yr for the core G113-0113B.

Unfortunately although every effort was made to process the samples for dinoflagellate cysts from Ga113-0113B using the same methodology as that for Ga113-2Ab (Harland et al., 2006) it became clear, as the results emerged, that there were significant differences in the raw counts between the two cores, possibly due to processing techniques and/or degradation during diagenetic processes. There was, however, no differences in the qualitative composition of the assemblages or in the general trends as seen within the cyst spectra (see later for further discussion). This is a perennial problem when samples are handled by two different laboratories some 10 years or more apart with different personnel, both of whom work to the highest standards. Data from both studies are available herein and in Harland et al. (2006) to facilitate further comparisons.

Both cores were treated quantitatively so as to calculate the numbers of dinoflagellate cyst species per gram of sediment (Table 1). The original dry weight of sample was noted and aliquot subsamples were taken for mounting and counting (Harland, 1989). Samples were counted from a single slide representing either 1 g of sediment or a fraction thereof using an ×40 objective of a Zeiss Axiolab microscope. The cysts per gram of sediment were subjected to statistical analyses by the software PAST, University of Oslo (Hammer et al., 2001). The Q-mode cluster analysis is used in biostratigraphy for clustering of samples, in contrast to the R-mode analysis, which is used for clustering of measured variables, e.g. associations of various species (Parker and Arnold, 1999). In our study the Q-mode cluster analysis was based on an unweighted pair group average (UPGMA) algorithm and a Euclidean distance as similarity measure. The UPGMA method creates clusters, which are joined based on the average distance between all members in the two groups (Hammer et al., 2001). The Euclidean distance is the most commonly used similarity measure in Q-mode clustering (Parker and Arnold, 1999). The UPGMA method was chosen because its dendrograms are known to show the highest cophenetic correlation (Sokal, 1986). Cophenetic correlation approaching 1.0 is a necessary criterion for optimality of the chosen clustering method (Davis, 1986). The Euclidean distance was also chosen because it reproduced dendrograms similar to those of Harland et al. (2006) for the core GA113-2Aa, which were created using the statistical package TILIAGRAPH (Grimm, 1987). In order to confirm the presence of observed cluster units we use a parallel multivariate technique i.e. factor analysis as recommended by Parker and Arnold (1999). A simple CABFAC (Calgary and Brown Factor Analysis: Klovan and Imbrie, 1971) Q-mode factor analysis with varimax rotation was performed on data of the most abundant dinoflagellate cysts. The varimax rotation is commonly used to maximise the variance in factor loadings i.e. to increase the explanatory value of factors (Parker and Arnold, 1999). The dinoflagellate cyst species contributing to the factor scores by >1 in absolute value, defined factor names associated with dominant components in the assemblages (Table 2). The raw counts, percentages, calculated cysts per gram of sediment and statistical data are held in open files at the Department of Earth Sciences, University of Gothenburg, Sweden, or from the senior author on request.

3. Results

3.1. Dinoflagellate cyst counts

It has previously been stated that the two cores under consideration were processed for dinoflagellate cysts by two different laboratories and some 10 years apart. It is, therefore not surprising that the results are somewhat different for very similar, if not identical, sediment sequences. An examination of the two dinoflagellate cyst spectra (Fig. 3) illustrates a number of features. Firstly there is a distinct increase in the numbers of cysts per gram in G113-0113B as compared to those published in Harland et al. (2006). Since this increase does not involve

Table 1
Gullmar Fjord Core G113-0113B Dinoflagellate cysts per gram of sediment.

Depth (cm)	1	2	3	4	5	6	7	8	9	10	12	14	16	18
Gonyaulacacean cysts														
Bitectatodinium tepikiense	0	0	200	100	300	100	100	100	0	0	100	100	0	0
Impagidinium pallidum	0	0	0	0	0	0	0	0	100	0	0	0	0	0
Lingulodinium polyedrum	1500	1000	1700	1800	1300	1900	600	2200	1500	3300	2500	2600	5700	8200
Protoceratium reticulatum	2000	2200	4100	2200	2100	2200	2200	2000	1300	3900	3200	2600	4600	4000
Spiniferites elongatus	0	0	0	0	100	0	0	0	0	0	0	100	0	0
Spiniferites frigidus	100	0	0	0	0	0	0	0	0	0	0	0	0	0
Spiniferites lazus	0	100	0	0	0	0	0	0	0	0	0	100	100	0
Spiniferites mirabilis	0	0	0	0	0	0	0	0	0	0	0	0	0	100
Spiniferites spp. indet.	400	300	1400	700	700	700	800	600	1100	600	400	300	700	400
Peridiniacean cysts														
Islandinium cezare	200	400	200	400	800	500	400	1000	500	700	1400	1000	900	500
Islandinium minutum	0	0	0	0	0	0	0	0	0	500	500	0	0	400
Lejeunecysta paratenella	0	0	0	0	0	0	100	100	0	0	0	0	0	0
Pentapharsodinium dalei	600	600	2300	1400	1800	2800	2700	3800	2900	3600	3900	3000	2700	1600
Protoperidinium compressum	0	100	0	0	0	0	0	0	0	0	0	0	0	0
Protoperidinium conicoides	0	0	0	100	0	100	0	0	0	0	0	0	0	0
Protoperidinium conicum	0	300	300	400	100	200	100	300	400	300	200	0	400	300
Protoperidnium divaricatum	0	100	0	0	0	0	0	0	100	0	0	0	0	0
Protoperidinium leonis	0	0	0	0	0	0	0	0	100	0	0	0	0	0
Protoperidinium oblongum	0	0	0	0	0	100	100	0	0	0	0	0	100	0
Protoperidinium pentagonum	0	0	100	100	100	100	100	0	0	0	0	100	0	0
Protoperidinium subinerme	0	0	100	0	0	0	0	0	0	0	0	0	0	0
Protoperidinium spp. indet. [R	1500	2100	2400	2000	3500	3300	3000	4600	3400	6000	5900	4000	7800	5400
Gymnodinialean cysts														
Gymnodinium nolleri	0	0	500	400	1100	500	500	800	900	700	1100	500	900	1100
Polykrikos kofoidii	100	400	300	200	700	300	200	600	600	400	700	100	200	0
Total	6400	7600	13,600	9800	12,600	12,800	10,900	16,100	12,900	20,000	19,900	14,500	23,600	2200

any species difference between the two records, the change is either down to differences in processing techniques or possibly inherent increased dinoflagellate cyst productivity. Without evidence to the contrary the first option is favoured for the moment. It is notoriously difficult to produce slides of a consistent quality especially where significant amounts of amorphous organic material (AOM) are present. Indeed, with the avoidance of oxidising reagents, these fjord sediments do contain large amounts of AOM. In particular, the difference in the numbers of *Lingulodinium polyedrum* (Stein 1883) Dodge 1989 (= *Lingulodinium machaerophorum* (Deflandre and Cookson 1955) Wall 1967) and *Protoceratium reticulatum* (Claparède and Lachmann 1859) Bütschli 1885 (= *Operculodinium centrocarpum* (Deflandre and Cookson 1955) Wall 1967), between the years 1993 and 2000, between the two cores is marked possibly resulting from processing differences noted above, subtle differences in sampling levels enhancing the effect of seasonality, a positive NAO or probably a combination of factors. However many of the trends seen in the Harland et al. (2006) are reflected in these younger sediments. For instance there is a decreasing trend in the occurrence of *Lingulodinium polyedrum*; a consistent presence of *Protoceratium reticulatum* throughout, together with *Bitectatodinium tepikiense* Wilson 1973. In contrast, certain changes are present within the younger sediments including the notable increase in *Pentapharsodinium dalei* Indelicato and Loeblich, III 1986, and *Islandinium* cf. *cezare* (de Vernal et al. 1989; Head et al. 2001). These increases occur around the late 1990s/ early 2000s and subsequently decrease from 2005 until the top of the core at 2013. Clearly there is no change in the dinoflagellate cyst assemblages across the suggested Holocene/Anthropocene boundary in Core Ga113-2Ab at ca. 38 cm (~1945).

Table 2
The clusters identified for core G113-0113B that correspond to those in Core Ga113-2Ab (Fig. 4) including their dinocyst species composition.

Core G113-0113B (this study)	Core Ga113-2Ab (Harland et al., 2006)
Cluster C:	Subunit 1a:
Bitectatodinium tepikiense	*Bitectatodinium tepikiense*
Lingulodinium polyedrum	*Lingulodinium polyedrum*
Protoceratium reticulatum	*Protoceratium reticulatum*
Pentapharsodinium dalei	*Islandinium* cf. *cezare*
Protoperidinium conicum	*Protoperidinium* round brown cysts
Polykrikos kofoidii	
Protoperidinium spp. indet (round, brown cysts)	
Cluster D:	Subunit 1b:
Protoceratium reticulatum	*Protoceratium reticulatum*
Pentapharsodinium dalei	*Pentapharsodinium dalei*
Lingulodinium polyedrum	*Islandinium* cf. *cezare*
Gymnodinium nolleri	*Gymnodinium nolleri*
Protoperidinium round brown cysts	*Protoperidnium conicum*
	Polykrikos kofoidii.
	Protoperidinium round brown cysts

3.2. Cluster analysis

The cluster analysis (Fig. 4) differentiates a number of units, some of which have been detailed already in Harland et al. (2006). It is of particular interest that subunits 1a and 1b for Ga113-2Ab compare well with clusters C and D from G113-0113B. These both occur within cluster unit F of Harland et al. (2013b) within the recent warming period. The major species compositions seem to correspond well between the two cores despite the differences in dinoflagellate cyst abundances as mentioned earlier. Two of the older clusters (~1991–2002) identified for G113-0113B by their dinoflagellate cyst spectrum correspond well to those in Core Ga113-2Ab (Table 2; Fig. 4) and are as follows:

- Cluster C (G113-0113B) corresponds with Subunit 1a (Ga113-2Ab)
- Cluster D (G113-0113B) corresponds with Subunit 1b (Ga113-2Ab)

Whilst the clusters look quite similar one of the notable features is the increased importance of *Pentapharsodinium dalei* in Core G113-

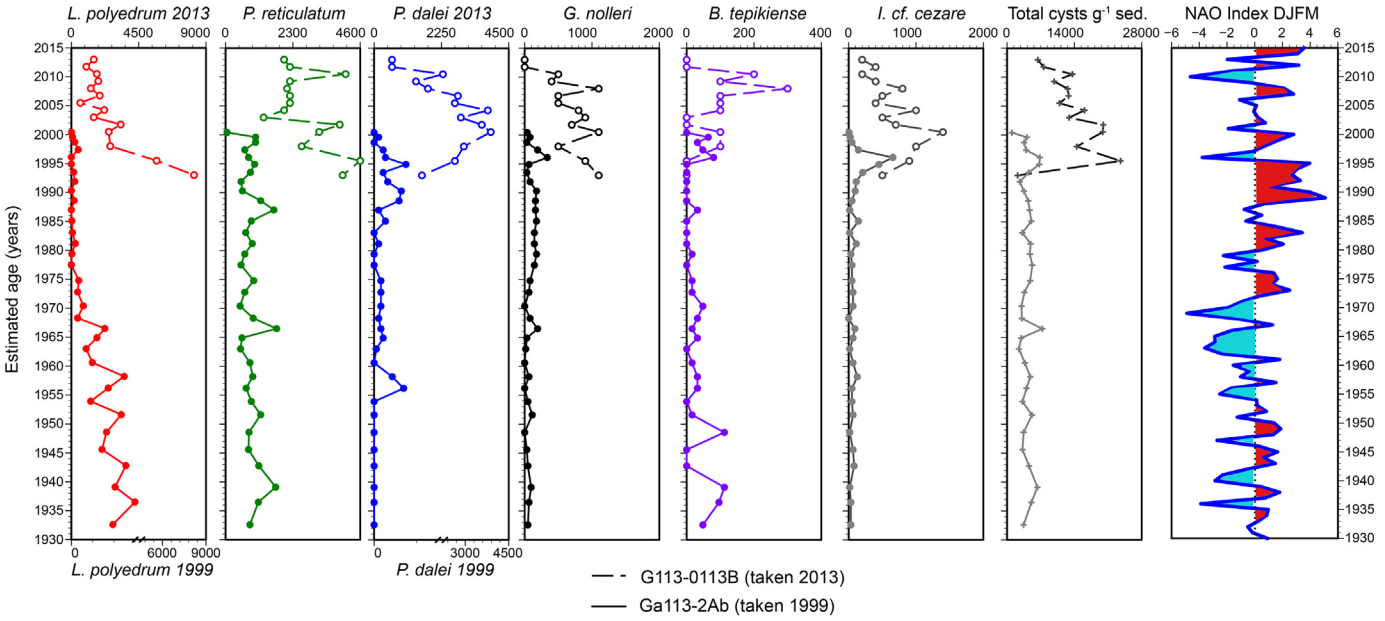

Fig. 3. Dinoflagellate cyst spectrum including the most important species (the full assemblage data are shown in Table 1). Cyst abundances are presented as cysts g^{-1} sediment. Winter NAO data come from: https://climatedataguide.ucar.edu/climate-data/hurrell-north-atlantic-oscillation-nao-index-station-based

0113B, an occurrence that is also reflected in the factor analysis (Fig. 5; see later).

In terms of the remaining clusters, representing the more recent part of core G113-0113B; Cluster B (~2003–2008) is characterised by lower contributions of *Lingulodinium polyedrum* and *Protoceratium reticulatum* as compared to Cluster C, lower numbers of *Gymnodinium nolleri* Ellegaard and Moestrup 1999, an increase in several *Protoperidinium* species and consistently higher *Pentapharsodinium dalei*, *Islandinium* cf. *cezare* and *Spiniferites* spp. indet. In Cluster A (2009–2013) *P. dalei*, *G. nolleri* and *Spiniferites* spp. indet. decrease in numbers toward the core top whilst *L. polyedrum* and *P. reticulatum* remain major components of the present day assemblage (see Erdtman, 1954; Persson et al., 2000).

3.3. Factor analysis

Factor analysis results in the subdivision of the dinoflagellate cyst record into three factors (characteristic assemblages) for both cores G113-0113B and Ga113-2Ab (Fig. 5 and Table 3). The distinguished factors explain a total 98 and 99% of the variance in both cores, respectively.

For the new dataset from the core G113-0113B, factor 1 (the dinoflagellate *P. dalei* + round, brown *Protoperidinium* spp. indet.) alone stands for 92.1% of explained variance, whereas factor 2 (*L. polyedrum* + round, brown *Protoperidinium* spp. indet.) and factor 3 (*P. reticulatum* + *Spiniferites* spp. indet) explain only 4.1 and 2.2% of the data respectively. In contrast, the old dataset from core Ga113-2Aa and its factor 1 (*L. polyedrum*) explains 88.1% of the variance, whereas factor 2 (*L. polyedrum* + round, brown *Protoperidinium* spp. indet.) and factor 3 (*P. reticulatum*) explain 9.7 and 1.5% of the data respectively.

Factor analysis when comparing both cores clearly defines a new factor of *P. dalei* (factor 1), specific only to the G113-0113B dataset (Fig. 5). Factors 2 and 3 in both datasets are represented by similar species giving the highest factor scores (Table 3). Factor 2, though it seems to have generally low factor scores in the G113-2Aa dataset, explains almost 10% of variance, which makes it significant for the core G113-2Aa (Fig. 5 and Table 3).

4. Discussion

Although the results of the dinoflagellate cyst analysis did not provide clear evidence of significant environmental change at the suggested Holocene/Anthropocene boundary in Gullmar Fjord, there are some interesting features that need comment. In particular the present study reinforces the results published earlier (Harland et al., 2006) in terms of the cluster analysis and the interpretation that followed. It is also interesting that factor analysis (Fig. 5) picks up the major dinoflagellate cyst assemblage changes in the late 1920s and at ~1970 described for GA113-2Aa by Harland et al. (2006). It remains, however, difficult to separate the various interacting environmental parameters that result in particular dinoflagellate cyst assemblages. However it does serve to illustrate the general complexity of temporal records over a high resolution temporal scale. The anticipation that clear environmental changes would be recognised across the base of the Anthropocene was not forthcoming nor were any clear trends resulting from either the action of the NAO, marine pollution and/or other global factors. It is, of course, naive to expect all biological entities to show change at this boundary, set up largely to provide a global and synchronous horizon.

The data presented herein, reveal a greater complexity than expected. In particular the relative importance of the small cyst *Pentapharsodinium dalei* as seen in both the cluster analysis and factor analysis is noteworthy and points to assemblage changes at around 15, 10 and 4 cm depth (~1997, ~2002 and ~2009, respectively) in core G113-0113B. This change is associated with assemblages dominated by *L. polyedrum* until ~1997, being replaced by *P. dalei* dominance between ~1997 and ~2002, before finally a decline of the latter is followed by an increase of both *L. polyedrum* and *P. reticulatum* (Fig. 5). The importance of *P. dalei* picked up in both statistical analyses suggests the results are not spurious but are of some significance. In this respect the increasing numbers of *P. dalei* in the early 1990s may be of particular interest. Increased numbers of *P. dalei* as recorded in Core G113-0113B through the early part of the 21st Century also appears to coincide with the increased frequency of negative winter NAO conditions implying cooler conditions from actualistic considerations, but perhaps more importantly increased nutrient supply from Ekman pumping favouring a spring phytoplankton bloom (Harland et al.,

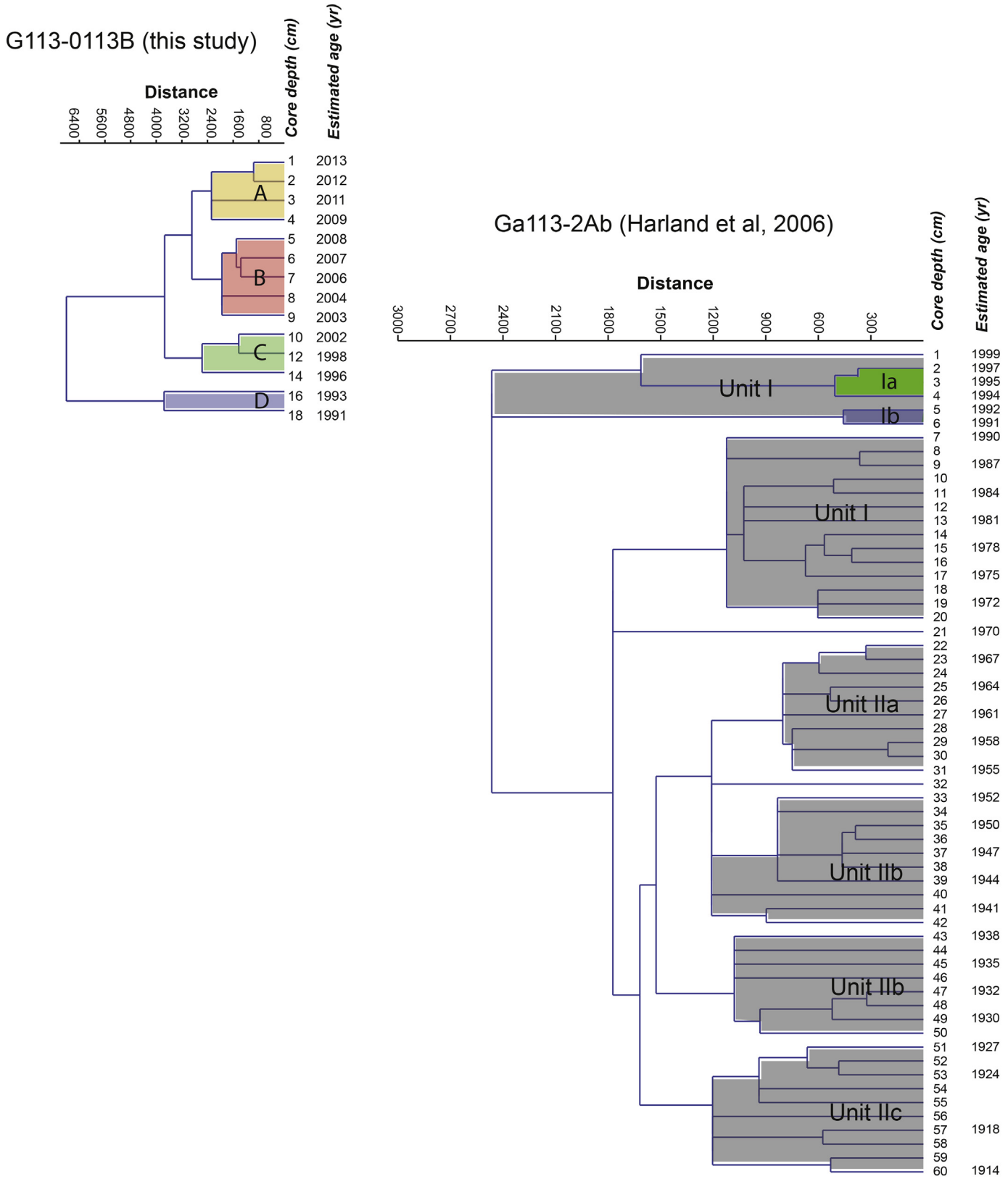

Fig. 4. Results of Q-mode cluster analysis performed for both cores G113-0113B and Ga113-2Ab. Note that older clusters C and D (core G113-0113B) in their dinocyst spectrum (Table 1) correspond to subunits of Ia and Ib (core Ga113-2Ab).

2013a,b). In both analyses *P. dalei* is seemingly the most important factor and this particular cyst is often noted as a cold temperature indicator (Zonneveld et al., 2013), and seen in increasing numbers through the 80s and 90s as a regional signal. Perhaps this trend is continued into the 2000s and 2010s. The co-occurrence of *P. dalei* with other colder water dinoflagellate cysts *B. tepikiense* and *I.* cf. *cezare* from 2000 to 2010 (Fig. 3), somewhat supports this hypothesis. Although currently in a positive phase of the winter NAO, the occasional reversal on an

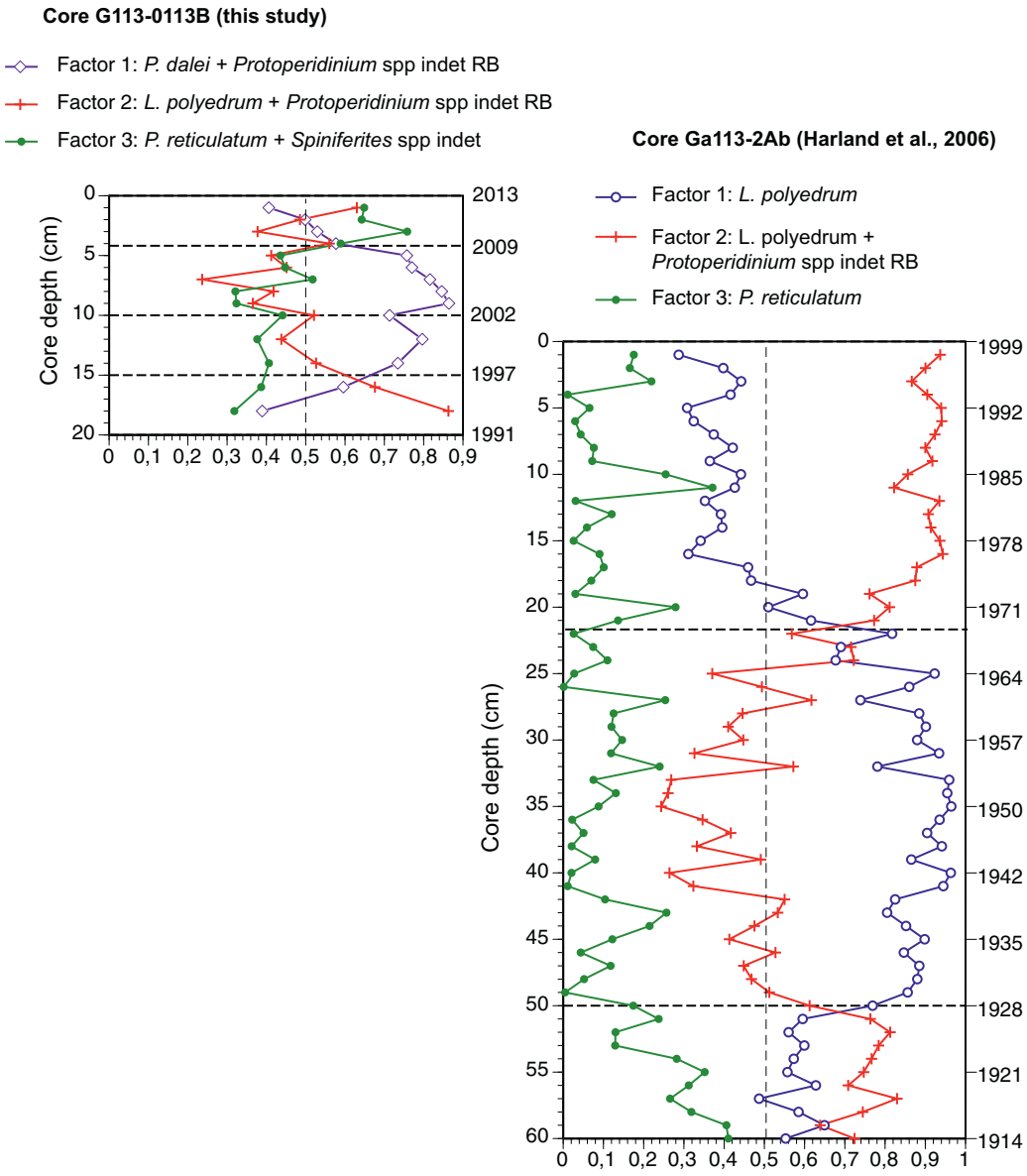
Core G113-0113B (this study)
Factor 1: P. dalei + Protoperidinium spp indet RB
Factor 2: L. polyedrum + Protoperidinium spp indet RB
Factor 3: P. reticulatum + Spiniferites spp indet
Core depth (cm)
0 5 10 15 20
2013 2009 2002 1997 1991
0 0,1 0,2 0,3 0,4 0,5 0,6 0,7 0,8 0,9
Core Ga113-2Ab (Harland et al., 2006)
Factor 1: L. polyedrum
Factor 2: L. polyedrum + Protoperidinium spp indet RB
Factor 3: P. reticulatum
Core depth (cm)
0 5 10 15 20 25 30 35 40 45 50 55 60
1999 1992 1985 1978 1971 1964 1957 1950 1942 1935 1928 1921 1914
0 0,1 0,2 0,3 0,4 0,5 0,6 0,7 0,8 0,9 1

Fig. 5. Results of CABFAC factor analysis performed for both cores G113-0113B and Ga113-2Ab. The horizontal dashed lines indicate major changes in the assemblages discussed in the text.

annual basis may be sufficient to allow upwelling from depth in the Skagerrak and Gullmar Fjord and a spring bloom containing *P. dalei*. Nutrient availability from upwelling is probably an important factor in driving dinoflagellate cyst assemblage change, given its effect on primary productivity within the phytoplankton (Lindahl et al., 2003; Tiselius et al., 2016), and may in itself indicate the strength of the north-easterly winds and high air pressure systems during negative NAO years. Indeed, when comparing our cyst spectrum from both cores to the winter NAO index (Fig. 3) it appears that *P. dalei* is become more abundant in the fjord during the period of the NAO index varying between its positive and negative phase. Also when considering core intervals with assemblage changes picked up by the factor analysis (see above), years 1997, 2002 and 2009 they too were all characterised either by negative or low positive NAO index (NAO data, 2017). Importantly work by Lindahl et al. (2009) of the Swedish Environmental Protection Agency concluded that there is a "direct link between primary production and nitrate concentrations in the mouth of the Gullmar Fjord". This is consistent with increased nitrate levels observed at 0–10 m in the fjord between 1995 and 2010 (Tiselius et al., 2016). In addition it was suggested that primary production is coupled with large climatic decadel fluctuations such as the winter NAO and subsequent nutrient regimes in the Skagerrak (Lindahl et al., 2003; Tiselius et al., 2016). The regime shift of the 1980s saw a warmer North Sea but interestingly less turbid water and improved water transparency (McQuatters-Gollop et al., 2007); a factor little discussed.

However the autecology of the species *P. dalei* is regarded as euryhaline with a distribution including polar to equatorial waters. It may be abundant where upper waters are <0 °C including some sea-ice with active upwelling (Zonneveld et al., 2013); possible confusion with the dinoflagellate *Ensiculifera imariense* Kobayashi and Matsuoka 1995 exists however, which may well have a profound effect on the global autecological data. In other words the environmental significance of the species is still far from clear especially at the scale needed to analyse change to disentangle the effects of global climate change, anthropomorphic effects, natural variability and some of the factors discussed above.

It is becoming increasingly clear that with ever more detailed high-resolution research and increasing knowledge of the ecology of dinoflagellates and their cysts, together with innovative molecular phylogenetic studies that a more sophisticated view of environmental change will emerge. This should enable the differentiation of dinoflagellate cyst assemblages in respect of their driving environmental control

Table 3
Factor scores for the old Ga113-2Ab and the new G113-0113B datasets. Bold italic numbers indicate dinoflagellate species with scores > 1 in absolute value, significantly contributing to the assemblages.

Core Ga113-2Ab				Core G113-0113B			
Dinoflagellates:	Factor 1	Factor 2	Factor 3	Dinoflagellates:	Factor 1	Factor 2	Factor 3
B. tepikiense	0,15	0,05	-0,39	*B. tepikiense*	0,10	-0,14	0,17
L. polyedrum	***4,04***	***1,46***	***1,44***	*I. pallidum*	0,04	-0,01	-0,02
P. reticulatum	***1,69***	-0,68	***−4,11***	*L. polyedrum*	−0,22	***4,53***	−0,22
S. bentorii	0,09	−0,16	0,30	*P. reticulatum*	−0,38	0,56	***4,58***
S. elongatus	0,10	0,01	−0,07	*S. elongatus*	0,03	−0,01	−0,03
S. mirabilis	0,05	0,02	−0,04	*S. frigidus*	−0,07	0,03	0,08
Spiniferites spp. indet.	0,71	−0,07	−0,06	*S. lazus*	−0,03	0,00	0,03
P. dalei	0,01	−0,13	0,24	*S. mirabilis*	−0,01	0,05	−0,02
I. cf. *cezare*	0,02	−0,24	0,20	*Spiniferites* spp. indet.	0,42	−0,52	***1,50***
I. minutum	0,00	0,00	0,00	*I. cezare*	0,73	0,04	−0,22
L. marieae	0,00	0,00	−0,01	*I. minutum*	0,06	0,19	−0,20
L. oliva	0,02	−0,02	−0,02	*L. paratenella*	0,06	−0,05	0,01
P. conicoides	−0,05	−0,12	−0,05	*P. dalei*	***3,51***	−0,83	0,52
P. conicum	0,22	−0,35	0,21	*P. compressum*	−0,04	−0,03	0,06
P. oblongum	0,03	−0,07	0,01	*P. conicoides*	0,00	0,01	0,05
P. pentagonum	0,00	−0,02	0,00	*P. conicum*	0,09	0,00	0,31
P. stellatum	0,00	0,00	0,00	*P. divaricatum*	0,00	−0,04	0,04
Protoperidinium spp. indet. *[RB]*	***1,08***	***−4,24***	***1,09***	*P. leonis*	0,04	−0,01	−0,02
G. nolleri	0,05	−0,22	−0,45	*P. oblongum*	0,05	−0,04	0,02
P. kofoidii	0,00	0,00	0,00	*P. pentagonum*	0,04	−0,07	0,14
P. schwartzii	0,06	−0,34	0,45	*P. subinerme*	−0,02	−0,03	0,09
				Protoperid. spp. indet. [RB]	***3,09***	***1,42***	−0,10
				G. nolleri	0,99	0,11	−0,41
				P. kofoidii	0,47	−0,38	0,18

over differing time scales from the annual to the decadal to the millennial. The presence of these assemblages in Swedish west coastal waters has the potential for monitoring change both locally and further afield in the adjacent North Sea and eastern North Atlantic. Disentangling all these factors is a major research aim and hence high resolution dinoflagellate cyst analysis will be a useful monitor of environmental change in this region of North West Europe.

5. Conclusions

The dinoflagellate cyst analysis of this small core in Gullmar Fjord, taken together with an earlier study (Harland et al., 2006) has led to a number of conclusions:

- The suggested Holocene/Anthropocene boundary at 1945 is not seen in the dinoflagellate cyst assemblages in Gullmar Fjord.
- Dinoflagellate cysts present are well known from the area and do not include thermophilic species better known from more southerly climes.
- There are significant changes in the dinoflagellate assemblages recognisable from the cyst spectra, cluster analysis and factor analysis including a marked increase in the numbers of *Pentapharsodinium dalei*, from around 1993 before declining toward 2010.
- Many of the changes may be interpreted as small scale alterations in the nutrient availability from the effect of the NAO and the strength of the north-easterly wind component driving upwelling from the Skagerrak.
- These data have the potential to provide a baseline for using dinoflagellate cysts to monitor environment change along the west coast of Sweden.

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